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COMPARISON OF MODIFIED VASCO X-2 WITH AISI 9310 - PRELIMINARY REPORT

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PRELIMINARY REPORT

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SUMMARY

Tests were conducted with spur gears and rolling-contact specimens made from CVM modified Vasco X-2 and VAR AISI 9310. Hardness measurements were made at elevated temperatures of these materials. The modified Vasco X-2 gears failed from tooth fracture due to crack formed during heat treatment. Failure of the AISI 9310 gears was by surface pitting. From RC bar specimen tests, the rolling-element fatigue life of AISI 9310 was approximately twice that of the modified Vasco X-2. At temperatures to approximately 422 K (300° F) there was no significant difference in hot hardness between the modified Vasco X-2 and AISI 9310.

INTRODUCTION

With advanced aircraft and helicopter transmission systems, gear temperatures are expected to exceed 394 K (250° F), the operating temperature limits of currently used gear materials such as AISI 9310 steel. Among the materials considered for advanced helicopter transmission systems is a material designated as "Modified Vasco X-2." This material was originally developed as a tool steel and was known as H-12 tool steel. The H-12 tool steel was later modified primarily by lowering the carbon content from 0.35 to 0.24 percent. The modified H-12 material was designated Vasco X-2. The original Vasco X-2 was a through hardened steel. In order to make the material more suitable for aircraft gearing, the carbon content was further lowered to a value ranging from 0.11 to 0.16 percent so that the gears could be case hardened with a soft core. Thus, the fracture toughness of the material for gear applications would theoretically be improved.

There are essentially three heat treatments available for this steel. The steel manufacturer has a recommended heat treatment (ref. 1). Another heat treatment was developed by Curtis Wright Corp. to carburize and harden gears (ref. 2). The Boeing Vartol Co. later developed their own heat treatment process which included a preoxidation process to prevent spotty carburization of the surfaces (ref. 3). The material with the Boeing Vertol heat treatment was used in the Heavy Lift Helicopter Program and the upgraded CH-47 helicopter. It was also proposed for the UTTAS Helicopter Program.

The objectives of the research reported herein was to (1) determine the performance of spur gears made from modified Vasco X-2, (2) compare the contact fatigue lives of modified Vasco X-2 with AISI 9310, and (3) compare hot hardness retention of Vasco X-2 with AISI 9310. In order to accomplish these objectives, tests were conducted with two lots of spur gears having different tempering temperatures but manufactured from one heat of consumable vacuum melted (CVM) modified Vasco X-2. One lot of spur gears manufactured from a single heat of vacuum arc remelted (VAR) AISI 9310 was also tested for comparison purposes. The gear pitch diameter was 8.89 centimeters (3.5 in.). Test conditions included a gear temperature of 350 K (170° F), maximum Hertz stresses of 153×10^{7}, 171×10^{7}, and 188×10^{7} N/m^{2} (222 000, 248 000, and 272 000 psi) and a speed of 10 000 rpm. Bench type rolling-element fatigue tests were also conducted to compare the modified Vasco X-2 material with AISI 9310. Test conditions were a speed of 12 500 rpm and a maximum Hertz stress of 483×10^{7} N/m^{2} (700 000 psi). Hardness measurements were made at elevated temperatures on samples of AISI 9310 and modified Vasco X-2 materials.

APPARATUS, SPECIMENS, AND PROCEDURE

Rolling-Element Tests

Rolling-contact (RC) fatigue tester. - The rolling-contact (RC) fatigue tester is shown in figure 1. A cylindrical test bar is mounted in the precision chuck. A drive means is attached to the chuck thereby driving the bar which in turn drives two idler disks. The disks are 19 centimeters (7.5 in.) in diameter and have a crown radius of 0.635 centimeter (0.25 in.). The load is applied by closing the disks against the test bar using a micrometer-threaded turnbuckle and a calibrated load cell. Lubrication is supplied by a drop system using a needle valve to control the flow rate. Several test runs can be made on one test bar by moving the bar position in the axial direction relative to disk contacts. The test bar is rotated at 12 500 rpm thus receiving 25 000 stress cycles per minute. The maximum Hertz stress was 483×10^{7} N/m^{2} (700 000 psi).

Test bar specimens. - The 7.62-centimeter (3-in.) long cylindrical test bars for fatigue tests were fabricated from modified Vasco X-2 and AISI 9310. The contacting disks were machined from a fourth heat of (CVM) AISI M-50 steel and heat-treated to the same hardness as the bars. The test bars were ground to a diameter of 0.95 centimeter (0.375 in.) with a surface finish of 0.13 to 0.2 micrometer (5 to 8 μin.) CLA. Similarly, the disks were ground to a disk diameter of 17 centimeters ($7\frac{1}{2}$ in.) and a crown radius of 0.635 centimeter (0.25 in.). The surface finish of the disks was the same as the test bars.

Test procedure - rolling-element. - Fatigue testing was performed in the RC rig. The test bar was installed and the disks were brought against the bar using a turnbuckle. A load was applied sufficient to allow the bar to drive the contacting disks, and the bar was accelerated to the desired speed.

When the disks and test bar were in thermal equilibrium at the desired bar temperature, the full load was applied. When a fatigue failure occurred, the rig and related instrumentationwere automatically shut down. The axial position of the test bar in the drive chuck was changed in order to use a new running track, and testing was resumed.

Hardness Measurements

Test specimens. - Specimens approximately 0.76 centimeter (0.300 in.) thick and 3.81 centimeters (1.5 in.) in diameter or 3.81 centimeters (1.5 in.) square were carburized and hardened so that a uniform case was formed on all surfaces of the specimen. A test surface free of the massive carbides that occur during heat treatment was formed by grinding 0.038 centimeter (0.015 in.) of material from the hardened surface. One speciment was sectioned into smaller pieces with a cutoff wheel. A copipus supply of coolant was supplied during this operation to prevent specimen overheating. One of these smaller specimens was used as the case test specimen.

Another specimen was used in the determination of the hardness gradient of the material. The hardness gradient was established from a series of Knoop hardness measurements made across a section at the center of the specimen. The results of these measurements are shown in figure 2 as Rockwell C equivalents converted from Knoop hardness numbers as a function of depth below the specimen surface.

The core of the specimen was defined to be the region of minimum hardness shown in figure 2. With the hardness gradient established, material was ground from another of the sectioned samples until the core surface was exposed (as indicated in fig. 2).

Apparatus and procedure. - Elevated temperature hardness measurements were made with a motorized Rockwell hardness tester fitted with an electric resistance furnace (shown in fig. 3). Errors due to major load dwell time were minimized by the automatic cycling operation of the motorized tester. A nitrogen cover gas was used within the furnace to inhibit surface oxidation and decarburization of the test specimens. A large size dial indicator was fitted to the tester so that readings to the nearest tenth of a point Rockwell "A" could be made.

All elevated temperature hardness measurements were made using the Rockwell "A" scale, 60 kilogram weight with a Rockwell C diamond indenter. These measurements were converted to their Rockwell C equivalents. Use of the Rockwell "A" scale for testing case hardened materials is necessary to minimize indenter depth of penetration. Maximum indenter penetration was 7.6×10^{-3} centimeter (0.003 in.) in the case and 0.01 centimeter (0.004 in.) in the core. Standard testing procedure required homogeneous material below the tested surface to a depth of 10 times the indenter penetration depth (ref. 4). All specimens tested met this requirement.

Specimen temperatures were measured by means of a thermocouple welded to the surface of the specimens. The specimens were stabilized for approximately 15 minutes at the test temperature before any measurements were taken. A minimum of three hardness measurements were made at each temperature.

Gear Tests

The gear fatigue tests were performed in the NASA Lewis Research Center's gear test apparatus (fig. 4). This test rig uses the four-square principle of applying the test gear load so that the input drive need only overcome the frictional losses in the system.

A schematic of the test rig is shown in figure 4(b). Oil pressure and leakage flow are supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes inside the slave gear, torque is applied to the shaft. This torque is transmitted through the test gears back to the slave gear, where an equal but opposite torque is maintained by the oil pressure. This torque on the test gears, which depends on the hydraulic pressure applied to the load vanes, loads the gear teeth to the desired stress level. The two identical test gears can be started under no load, and the load can be applied gradually, without changing the running track on the gear teeth.

Separate lubrication systems are provided for the test gears and the main gearbox. The two lubricant systems are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen was the seal gas. The test gear lubricant is filtered through a 5-micron nominal fiber-glass filter. The test lubricant can be heated electrically with an immersion heater. The skin temperature of the heater is controlled to prevent overheating the test lubricant.

A vibration transducer mounted on the gearbox was used to automatically shut off the test rig when a gear-surface fatigue occurs. The gearbox was also automatically shut off if there is a loss of oil flow to either the main gearbox or the test gears, if the test gear oil overheats, or if there is a loss of seal gas pressurization.

The test rig is belt-driven and can be operated at several fixed speeds by changing pulleys. The operating speed for the tests reported herein was 10 000 rpm.

Lubrication was supplied to the inlet mesh of the gear set by jet lubrication. Lubricant flow rate was held constant at 800 cubic centimeters per minute. The lubricant inlet temperature was constant at 310±6 K ($115^{\circ}\pm10^{\circ}$ F), and the lubricant outlet temperature was nearly constant at 350±3 K ($170^{\circ}\pm5^{\circ}$ F). This outlet temperature was measured at the outlet of the test-gear cover. A nitrogen cover gas was used throughout the test as a baseline condition which allowed testing at the same conditions at much higher temperatures without oil degradation. This cover gas also reduced the effect of the oil additives on the gear surface boundary lubrication by reducing the chemical reactivity of the additive-metal system by excluding oxygen (ref. 5).

The test gears were cleaned to remove the preservative and then assembled on the test rig. The test gears were run in an offset condition with a 30×10^{-4} meter (0.12 in.) tooth-surface overlap go give a load surface on the gear face of 28×10^{-4} meter (0.11 in.) of the 64×10^{-4} meter (0.250 in.) wide gear, thereby allowing for edge radius of the gear teeth. By testing both faces of the gears, a total of four fatigue tests could be run for each set of gears. All tests were run-in at a normal load of 2714×10^{2} newtons per meter (1550 lb/in.) for 1 hour. The normal load was then increased to 6161×10^{2} newtons per meter (3518 lb/in.) with a 171×10^{7} newton per square meter (248 000 psi) pitch-line Hertz stress. At the pitch-line load the tooth bending stress was 2.26×10^{8} newtons per square meter (32 700 psi) if plain bending is assumed. However, because there is an offset load there is an additional stress imposed on the tooth bending stress. Combining the bending and torsional moments gives a maximum stress of 2.86×10^{8} newtons per square meter (41 500 psi).

The test gears were operated at 10 000 rpm, which give a pitch-line velocity of 46.55 meters per second (9163 ft/min). Lubricant was supplied to the inlet mesh at 8×10^{-4} cubic meters (0.21 gal) per minute at 310±6 K (115±10° F). The tests were continued 24 hours a day until they were shut down automatically by the vibration-detection transducer located on the gearbox, adjacent to the test gears. The lubricant was circulated through a 5-micron fiber-glass filter to remove wear particles. A total of 38×10^{-4} cubic meters (1 gal) of lubricant was used for each test and was discarded, along with the filter element, after each test. Inlet and outlet oil temperatures were continuously recorded on a strip-chart recorder.

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of reference 6. It was assumed, for this film thickness calculation, that the gear temperature at the pitch line was equal to the outlet oil temperature and that the inlet oil temperature to the contact zone was equal to the gear temperature, even though the oil inlet temperature was considerably lower. It is probable that the gear surface temperature could be even higher than the oil outlet temperature, especially at the end points of sliding contact. The EHD film thickness for these conditions was computed to be 0.33 micrometer (13 μin.), which gave a ratio of film thickness to composite surface roughness (h/σ) 0.55 at the 171×10^{7} newtons per square meter (248 000 psi) pitch-line Hertz stress.

Test Lubricants

All tests conducted with gears manufactured from modified Vasco X-2 were lubricated with a single batch of synthetic paraffinic oil. The physical properties of this lubricant are summarized in table I. Five percent of an extreme pressure additive, designated Lubrizol 5002 (partial chemical analysis given in table II), was added to the lubricant.

The AISI 9310 gears were tested with a single batch of a super-refined naphthenic mineral oil having proprietary additives (antiwear, antioxidant, and antifoam). The physical properties of this lubricant are also summarized in table I. Five percent of an extreme pressure additive, designated Anglamol 81 was added to this lubricant. A partial chemical analysis of this additive is given in table II.

The rolling-element fatigue tests with the RC bar specimens of both materials were lubricated with a MIL-L-7808 type lubricant. The fluid comprised a mixture of two base stocks, a diester plus a TMP polyester. The additives in this fluid included anti-oxidants, load-carrying additives, metal passivators, hydrolytic stability additive, and a silicone anti-foam additive. The types and levels of the additives were proprietary.

Test Gears and Materials

Modified Vasco X-2. - The test gears and RC bar specimens manufactured from modified Vasco X-2 were from a single material heat. This heat of material was the same as that used for the manufacture of gears for the Heavy Lift Helicopter transmissions. The chemical composition of the modified Vasco X-2 is given in table III.

As previously discussed, this material was originally developed as a through hardened tool steel having a carbon content of approximately 0.24 percent. In order to make this material more suitable for aircraft gear application, the carbon content was lowered to a value ranging from 0.11 to 0.16 percent. Thus, the fracture toughness of the material for gear applications would be theoretically improved.

The modified Vasco X-2 test gears were case carburized, hardened and tempered in accordance with the heat-treatment given in table IV. The gears were rough machined 3.8×10^{-4} meter (0.015 in.) oversized before carburizing so that the outer layer of heavy carbide concentration could be ground away, leaving a hardend case depth of 6×10^{-4} to 8×10^{-4} meter (0.025 to 0.030 in.).

Figure 5(a) is a cross section through the gear tooth showing the carburized surface and core grain structure. Figure 5(b) is an enlarged view of the case and course core grain structure typical of the modified Vasco X-2 material.

Dimensions for the test gears are given in table V. The case hardness of the finish gear and the RC specimens was Rockwell C 61 to 63 and the case hardness was Rockwell C 43. All gears had a nominal surface finish on the tooth face of 0.406 micrometer (16 μ in.) CLA and a standard 20° involute tooth profile. There was no crowning or tip relief of the gear teeth.

AISI 9310. - The AISI 9310 gears were manufactured from a single heat of vacuum arc remelted (VAR) AISI 9310. The chemical composition of the AISI 9310 gears is given in table III. The RC bar specimens were manufactured from a second heat of material. The chemical composition for this second heat of material is also given in table III. The heat treatment for the AISI 9310 gears is given in table VI. A photomicrograph of etched and polished surface of the AISI 9310 gear is shown in figure 6. The case hardness of the gears was Rockwell C 62 to 64. The gear core hardness was Rockwell C 35 to 40. For the RC bar specimen the case hardness was Rockwell C 60 to 63. The specimen core hardness was Rockwell C 41.

Dimensions for the AISI 9310 test gears are given in table V. All gears have a nominal surface finish on the tooth face of 0.406 micrometer (16 μin.) rms and a standard 20° involute profile with tip relief. Tip relief was 0.0013 centimeter (0.005 in.) starting at the last 30 percent of the active profile The gears were also crowned.

RESULTS AND DISCUSSION

Rolling-Element Fatigue

Fatigue tests were conducted with the modified Vasco X-2 and the AISI 9310 materials with a MIL-L-7808 lubricant. Test temperature was ambient room temperature, a maximum Hertz stress of 483×10^{7} N/m^{2} (700 000 psi) and a speed of 12 500 rpm or 25 000 stress cycles per minute. The results of these tests are shown in figure 7 and summarized in table VII. The 10-percent lives from the Weibull plots in figure 7 (the life which 90 percent of the test bars will survive) were used for comparison purposes. The rolling-element fatigue life of the VAR AISI 9310 was approximately twice that of the CVM modified Vasco X-2.

The confidence number for these data given in table VII was 84. This confidence number indicates that 84 percent of the time the 10-percent fatigue life with AISI 9310 will be greater than the 10-percent fatigue life with the modified Vasco X-2 material.

Hardness Retention

The ability of a material to retain its hardness at elevated temperature, in view of its direct influence on rolling-element fatigue life, is an important design criterion for high performance gears and rolling-element bearings such as those found in helicopter transmissions. Apart from a potential reduction in fatigue life, low hardness of rolling-element bearing components can result in permanent surface deformation and distress during operation leading to premature failure.

Hot-hardness measurements were made on the case and core areas of modified Vasco X-2 and AISI 9310. The results of these measurements are shown in figures 8(a) and 9(a) as plots of hardness against specimen temperature for each material. To eliminate room temperature hardness differences, the data of figures 7(a) and 8(a) was normalized in figures 8(b) and 9(b). Figures 8(b) and 9(b) are plots of the change in hardness from room temperature hardness as a function of specimen temperature. These data indicate the similarity between changes in case and core hardness with temperature.

The individual normalized short-term hot-hardness curves for the case from figures 8(b) and 9(b) are combined for comparison in figure 10. AISI 9310 experienced a relatively rapid decrease in material hardness with temperature. The modified Vasco X-2 had a more gradual decrease in material hardness with temperature up to 811 K (1000° F). These data are consistent with the tempering characteristics of these two steels. At temperatures to approximately 422 K (300° F) there was no significant difference in hardness between the materials.

In figure 11 modified Vasco X-2 is compared with data from reference 7 for a large number of through hardened high-speed tool steels. Vasco X-2 is similar to those tool steels in that it also is a precipitation hardening alloy. Figure figure 11 it is evident that the Vasco X-2 steel has hot-hardness characteristics similar to the through-hardened high-speed tool steels up to 644 K (700° F) above which Vasco X-2 is inferior.

The changes in hardness as a function of temperature for Vasco X-2 and AISI 9310 satisfy the equation developed in reference 8 for the prediction of hardness with change in temperature

$$(Rc)_T = (Rc)_{RT} - \alpha\ \Delta T^{\beta}$$

where

$(Rc)_T$	Rockwell C hardness at temperature
$(Rc)_{RT}$	Rockwell C hardness at room temperature
ΔT	change in temperature, $T_T - T_{RT}$
T_T	operating temperature, K; $^\circ$F
T_{RT}	room temperature, K; $^\circ$F

α temperature proportionality factor, $(K)^{-\beta}$; $(^{o}F)^{-\beta}$

β exponent

The values for α and β modified Vasco X-2 and AISI 9310 are summarized in table VIII. The equation is valid for AISI 9310 from 298 to 589 K (70^{o} to 600^{o} F) and for modified Vasco X-2, from 294 to 811 K (70^{o} to 1000^{o} F).

Gear tests. - Tests were run with three groups of CVM AISI 9310 gears at three load conditions with a super-refined napththenic mineral oil having an additive package. The results of these tests are shown in figure 12 and are summarized in table IX along with the test conditions. All surfaces of the AISI 9310 gears were carburized. Failure of the AISI 9310 gears were by surface pitting or spalling, which were of subsurface origin on or about the pitch-line of the gear tooth. No fracture of the gear teeth occurred. A typical spalled tooth is shown in figure 13.

Groups of gears made from modified Vasco X-2 carburized and hardened were tested under a load of 171×10^{7} N/m^{2} (248 000 psi) and 153×10^{7} N/m^{2} (222 000 psi). One group was tempered at 589 K (600^{o} F). A second group was tempered at 783 K (950^{o} F). The gears were lubricated with a synthetic paraffinic oil.

A test comprising one pair of gears tempered at 589 K (600^{o} F) were run at a maximum Hertz stress of 171×10^{7} (248 000 psi). The gears failed within 30 minutes after startup. In the test 6 and 12 teeth failed on each gear, respectively. Failure was by tooth fracture at the tip of the tooth instead of at the root which normally would be expected of gears which fail by fracture fatigue. Typical tooth fractures occurring in the modified Vasco X-2 gears are shown in figure 14.

A second test comprising one pair of gears tempered at 589 K (600^{o} F) were run at a maximum Hertz stress of 153×10^{7} N/m^{2} (222 000 psi). These gears also failed in the same manner and within the same time as those of the first test.

Three tests of modified Vasco X-2 gears tempered at 983 K (950^{o} F) were run. One test was run at a maximum Hertz stress of 171×10^{7} N/m^{2} (248 000 psi). The gears failed by fracture within one-half hour. Two additional tests were run at 153×10^{7} N/m^{2} (222 000 psi). These gears failed by fracture within one-half hour and 3 hours, respectively.

Two unfailed teeth on a failed gear were cross-sectioned in two directions, across the width of the tooth and through the tooth profile. A cross section of a tooth is shown in figure 14. The section through the width of the tooth revealed a crack around each corner of the tooth. Since this gear, which was run on one side, had cracks on both corners, it was theorized that the cracks may have been present before the gears were run. Another gear tooth from an unrun gear was sectioned and the same corner cracks were present in this gear as shown in figure 16. From this figure, it was evident that the cracks had developed during the heat treat process giving rise to very early failures during tests.

The gears were carburized on all surfaces. It is theorized that during the carburized process, the expansion of the surface material was too great for the core material. This resulted in cracks developing at the ends of the teeth where the internal tensile stress would be highest. The AISI 9310 gears were run with all surfaces carburized without the problem of cracks developing at the edges of the teeth.

Additional modified Vasco X-2 gears are being fabricated with all surfaces except the working flanks masked off for carburizing. It is theorized that this procedure should minimize the problem of crack formation. The apparent sensitivity of the modified Vasco X-2 material to the case carburizing process casts doubts on the practicality of using this material at the present time beyond laboratory and prototype testing.

SUMMARY OF RESULTS

Tests were conducted with two lots of spur gears having different tempering temperatures but manufactured from one heat of consumable vacuum melted (CVM) modified Vasco X-2. One lot of spur gears manufactured from a single heat of vacuum arc remelted (VAR) AISI 9310 was also tested for comparison purposes. Test conditions included a gear temperature of 350 K (170° F), maximum Hertz stresses of 153×10^{7}, 171×10^{7}, and 188×10^{7} N/m^{2} (222 000, 248 000, and 272 000 psi) and a speed of 10 000 rpm. Bench type rolling-element fatigue tests were also conducted to compare the modified Vasco X-2 material with AISI 9310. Test conditions were a speed of 12 500 rpm and a maximum Hertz stress of 483×10^{7} N/m^{2} (700 000 psi). Hardness measurements were made at elevated temperatures on samples of AISI 9310 and modified Vasco X-2 materials. The following results were obtained:

1. Crack formation at the tips of the gear teeth during the carburizing process of the modified Vasco X-2 resulted in fracture of the gear teeth after a period of less than 1 hour (600 000 revolutions) of operations under test conditions.

2. The life of the AISI 9310 gears at a 90-percent probability of survival were 39.3, 19, and 7.1 hours (23.6, 11.4, and 4.3 millions of resolutions) at 1531×10^6, 1710×10^6, and 1875×10^6 N/m^2 (222 000, 248 000, and 272 000 psi), respectively.

3. Failure of the AISI 9310 gears was by surface pitting with no tooth fracture occurring.

4. The rolling-element fatigue life of the VAR AISI 9310 was approximately twice that of the CVM modified Vasco X-2.

5. At temperatures to approximately 422 K (300° F) there was no significant difference in hot hardness between the modified Vasco X-2 and AISI 9310 materials.

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TABLE I. - LUBRICANT PROPERTIES

Property	Synthetic paraffinic oil plus additives	Diester plus TMP[a] polyester plus additives	Super-refined naphthenic oil plus additives
Kinematic viscosity, cm^2/sec (cs) at:			
244 K (-20° F)	2500×10^{-2} (2500)	580×10^{-2} (580)	-------------
311 K (100° F)	31.6×10^{-2} (31.6)	14.8×10^{-2} (14.8)	73×10^{-2} (73)
372 K (210° F)	5.7×10^{-2} (5.7)	3.7×10^{-2} (3.7)	7.7×10^{-2} (7.7)
477 K (400° F)	2.0×10^{-2} (2.0)	1.2×10^{-2} (1.2)	1.6×10^{-2} (1.6)
Flash point, K ($^{\circ}$F)	508 (455)	491 (425)	489 (420)
Fire point, K ($^{\circ}$F)	533 (500)	527 (490)	664 (735)
Pour point, K ($^{\circ}$F)	219 (-65)	213 (-75)	(-35)
Specific gravity	0.8285	0.950	
Vapor pressure at 311 K (100° F), mm Hg (or torr)	0.1	10^{-5}	0.01
Specific heat at 311 K (100° F), J/(kg)(k) (Btu/(lb)($^{\circ}$F))	676 (0.523)	608 (0.470)	582 (0.450)

[a]Tri-methyl propane.

TABLE II. - PROPERTIES OF LUBRICANT ADDITIVES

Additive property	Lubrizol 5002	Anglamol 81
Percent phosphorous by weight	0.60	0.66
Percent sulfur by weight	18.5	13.41
Specific gravity	1.015	0.982
Kinematic viscosity at 372K (210° F), cm^2/sec (cS)	10.3×10^{-2} (10.3)	29.5×10^{-2} (29.5)

TABLE III. - CHEMICAL COMPOSITION OF TEST

MATERIALS BY PERCENT WEIGHT

Element	Modified Vasco X-2 gears and RC specimens	AISI 9310	
		Gears	RC specimens
Carbon (core)	0.12	0.10	0.09
Manganese	.29	.63	.66
Phosphorous	.012	.005	.012
Sulfur	.008		.005
Silicon	.88	.27	.23
Copper	.09	.13	.10
Chromium	4.95	1.21	1.36
Molybdenum	1.34	.12	.15
Vanadium	.42	-----	-----
Nickel	.06	3.22	3.16
Cobalt	.02	-----	-----
Tungsten	1.32	-----	-----
Iron	Balance	Balance	Balance

TABLE IV. - HEAT TREATMENT PROCESS FOR CONSUMABLE VACUUM MELTED (CVM) MODIFIED VASCO X-2

Step	Process	Temperature		Time, hr
		K	°F	
1	Rough machine, 2.54×10^{-4} - 3.56×10^{-4} M (0.010 - 0.014 in.)			
2	Preheat in air	1117	1550	Hold
3	Preoxidation in air	1283	1850	0.5
4	Carburize in 1 percent potential for 1×10^{-3} M (0.040 in.) depth	1200	1700	
5	Austenitize in protective atmosphere	1283	1850	1
6	Deep freeze	200	-100	3
7	Triple temper			
	Group 1	589	600	2 ea
	Group 2	783	950	2 ea

TABLE V. - GEAR DATA

[Gear tolerance per AGMA class 12.]

Number of teeth	28
Diametral pitch	8
Circular pitch, cm (in.)	0.9975 (0.3927)
Whole depth, cm (in.)	0.762 (0.300)
Addendum, cm (in.)	0.318 (0.125)
Chrodal tooth thickness reference, cm (in.)	0.485 (0.191)
Pressure angle, deg	20
Pitch diameter, cm (in.)	8.890 (3.500)
Outside diameter, cm (in.)	9.525 (3.750)
Root fillet, cm (in.)	0.102 to 0.152 (0.04 to 0.06)
Measurement over pins, cm (in.)	9.603 to 9.630 (3.7807 to 3.7915)
Pin diameter, cm (in.)	0.549 (0.216)
Backlash reference, cm (in.)	0.0254 (0.010)

TABLE VI. - HEAT TREATMENT PROCESS FOR VACUUM

ARC REMELTED (VAR) AISI 9310

Step	Process	Temperature		Time, hr
		K	°F	
1	Carburize	1172	1650	8
2	Air cool to room temperature	----	----	---
3	Copper plate all over to prevent decarburization	----	----	---
4	Reheat	922	1200	2.5
5	Air cool to room temperature	----	----	---
6	Austenitize	1117	1550	2.5
7	Oil quench	----	----	----
8	Subzero cool	189	-120	3.5
9	Double temper	450	350	2 ea
10	Finish grind	----	----	---
11	Stress relieve	450	350	2

TABLE VII. - FATIGUE-LIFE RESULTS IN ROLLING-CONTACT (RC) TESTER

[Speed, 25 000 stress cycles per min.; maximum hertz stress, 4823×10^6 N/m^2 (700 000 psi); lubricant, MIL-L-7808, temp., ambient.]

Material	Life, millions of stress cycles		Weibull slope	Failure index (a)	Confidence number at 10-percent life level (b)
	10-Percent life	50-Percent life			
Modified Vasco X-2	63	148	2.2	20 out of 20	84
AISI 9310	140	570	1.4	6 out of 20	----

[a]Number of fatigue failures out of number of specimens tested.
[b]Percentage of time that 10-percent life obtained with AISI 9310 will have the same relation to the 10-percent life obtained with modified Vasco X-2.

TABLE VIII. - TEMPERATURE PROPORTIONALITY FACTORS α AND EXPONENTS β FOR FIVE CASE HARDENED STEELS

$$\left[(Rc)_T = (Rc)_{RT} - \alpha\,\Delta T^{\beta}.\right]$$

Material	Temperature range		α		β	
	K	^oF	K	^oF	K	^oF
AISI 9310	294 to 589	70 to 600	1.92×10^{-5}	0.50×10^{-5}	2.3	2.3
Vasco X-2	294 to 811	70 to 1000	1.4×10^{-5}	0.38×10^{-5}	2.2	2.2

TABLE IX. - SUMMARY OF FATIGUE LIFE RESULTS WITH 8.89-CM (3.5-IN.) PITCH DIAMETER SPUR GEARS AT THREE LOADS

[Material, VAR AISI 9310 steel; speed, 10 000 rpm; lubricant, superrefined naphthenic mineral oil with additive package.]

Transmitted tangential load, wt, lb/in.	Maximum Hertz stress, N/M^2, $lb/in.^2$	Gear set life, millions of revolutions, hr						Weibull slope	Failure index[a]
		L_{10}			L_{50}				
		Lower 90-percent confidence limit	Experi-mental	Upper 90-percent confidence limit	Lower 90-percent confidence limit	Experi-mental	Upper 90-percent confidence limit		
463×10^3 (2645)	1531×10^6 (222×10^3)	12.4 (20.7)	23.6 (39.3)	44.8 (74.6)	47.9 (79.9)	63.8 (106.4)	85 (141.6)	1.9	19 out of 19
578×10^3 (3305)	1710×10^6 (248×10^3)	7.1 (11.8)	11.4 (19)	18.2 (30.4)	19.2 (32)	23.8 (39.6)	29.3 (48.8)	2.6	19 out of 19
694×10^3 (3966)	1875×10^6 (272×10^3)	2.8 (4.6)	4.3 (7.1)	6.4 (10.7)	6.7 (11.2)	8.1 (13.5)	9.8 (16.3)	2.9	19 out of 19

[a]Number of gear failures out of number of gears tested.

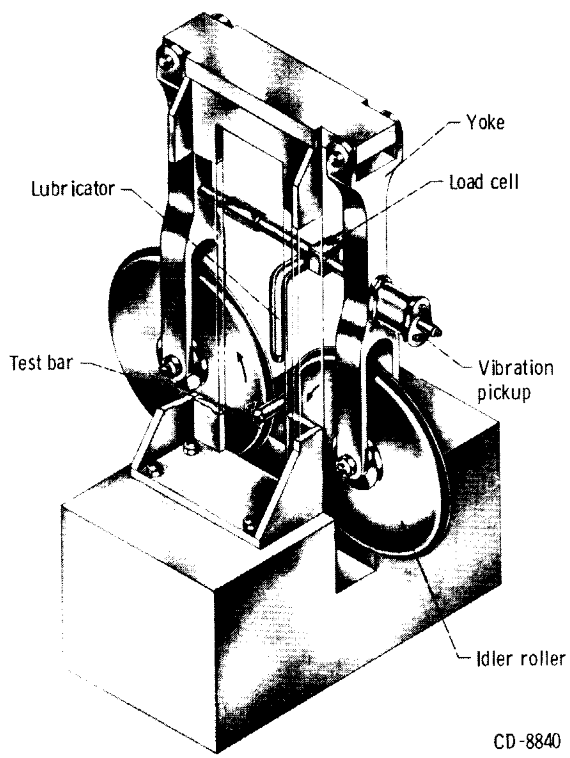


Figure 1. - Rolling-contact fatigue apparatus.

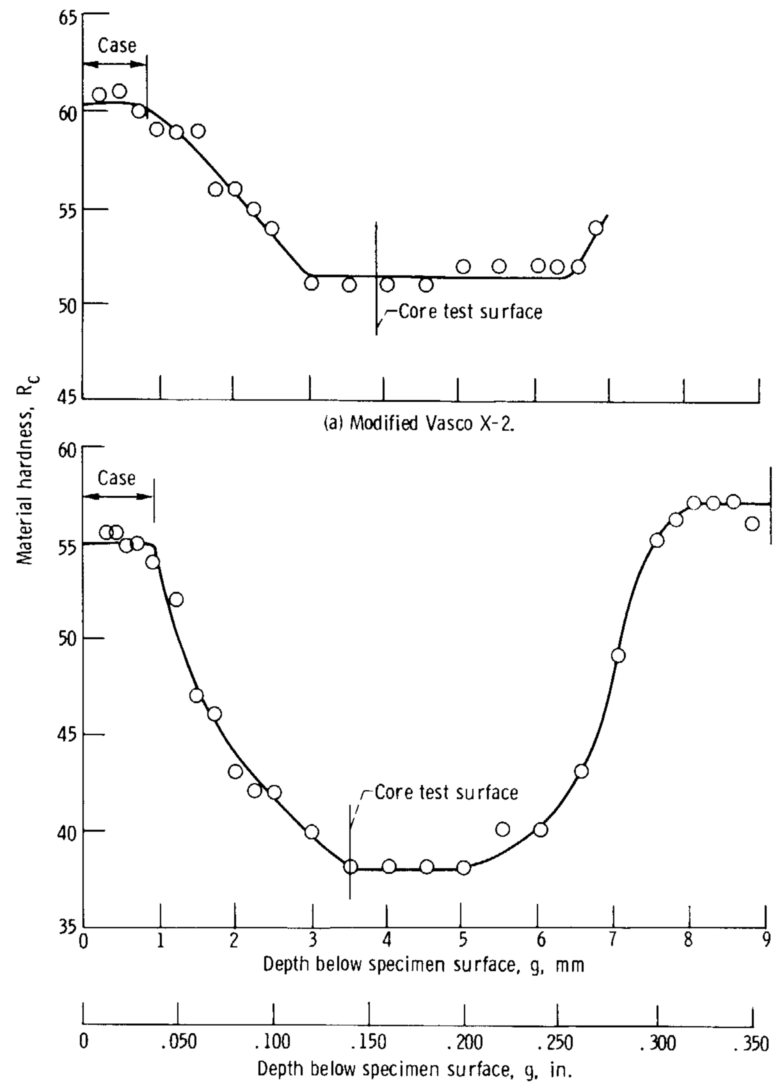


Figure 2. - Microhardness gradient (room temperature Knoop hardness measurements converted to Rockwell C equivalents.

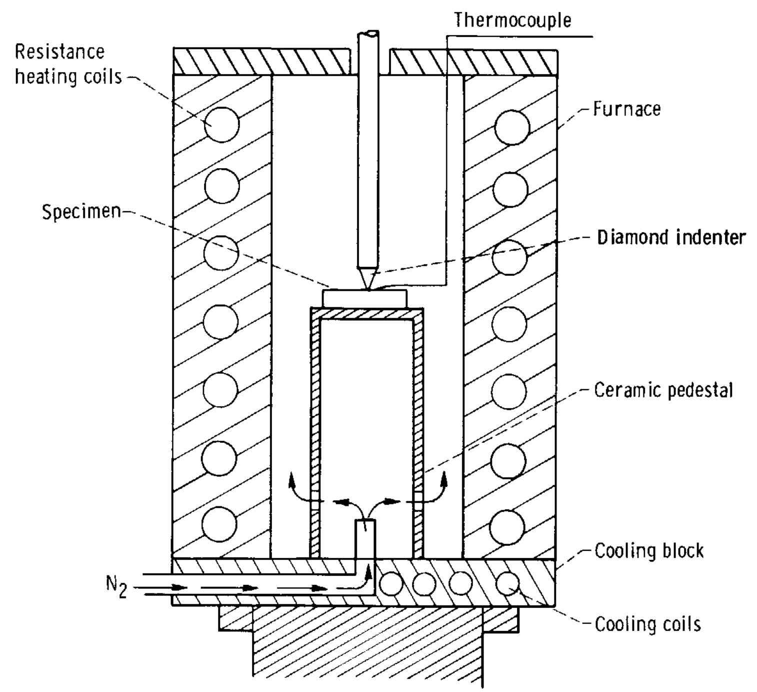
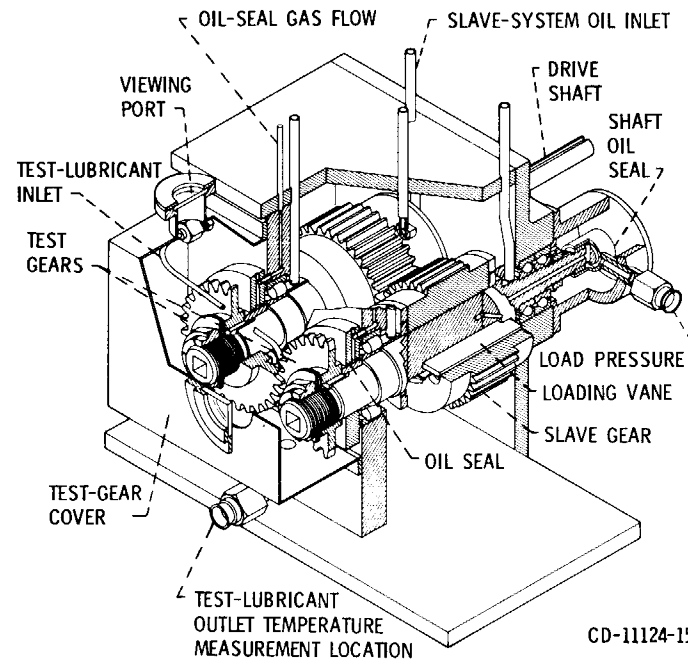
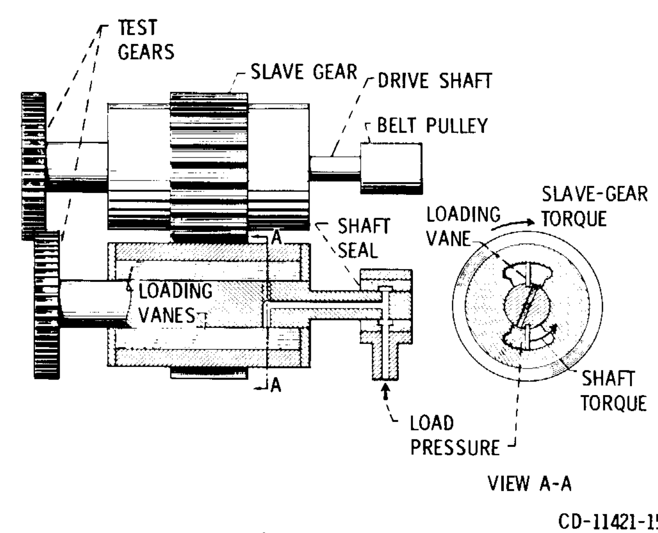


Figure 3. - Cross section of hot-hardness tester.

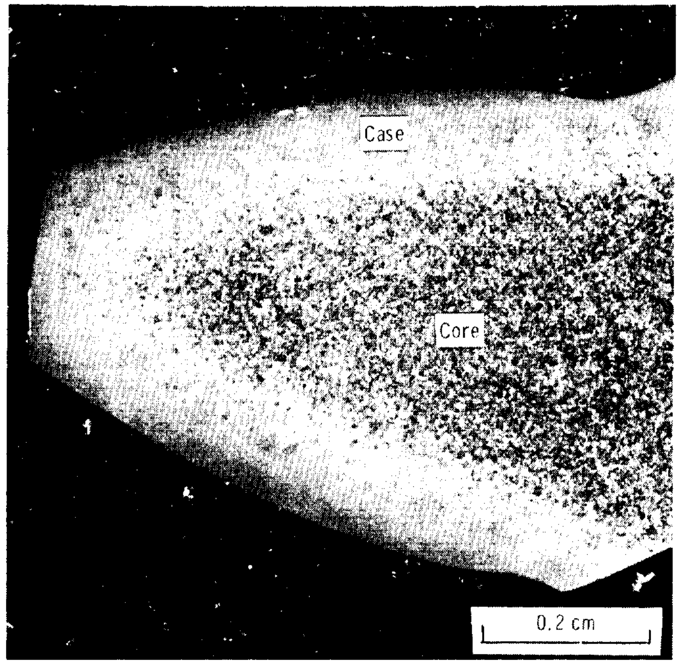


(a) CUTAWAY VIEW.



(b) SCHEMATIC DIAGRAM.

Figure 4. - NASA Lewis Research Center's gear-fatigue test machine.



(a) Gear tooth.

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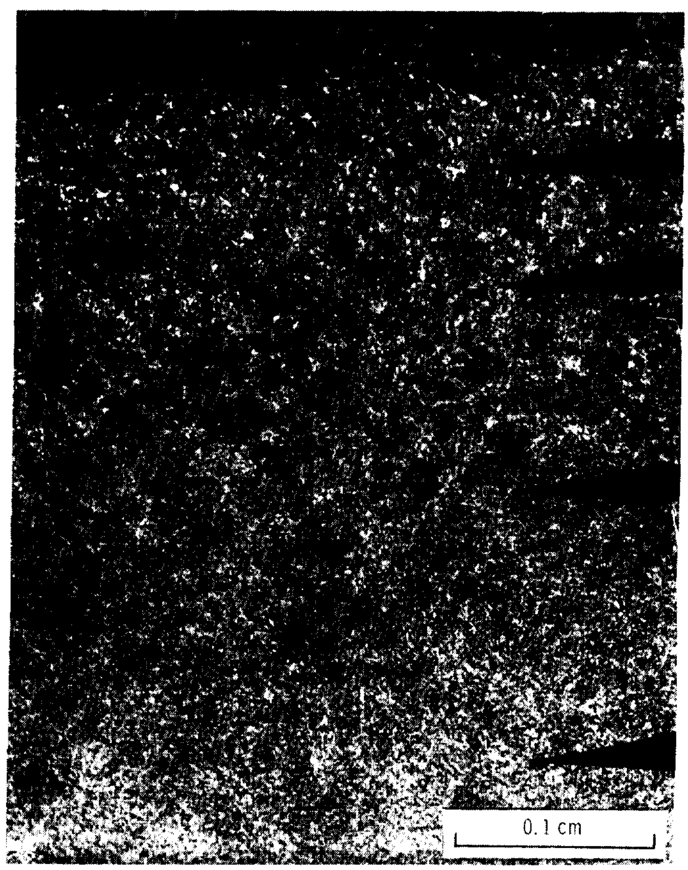
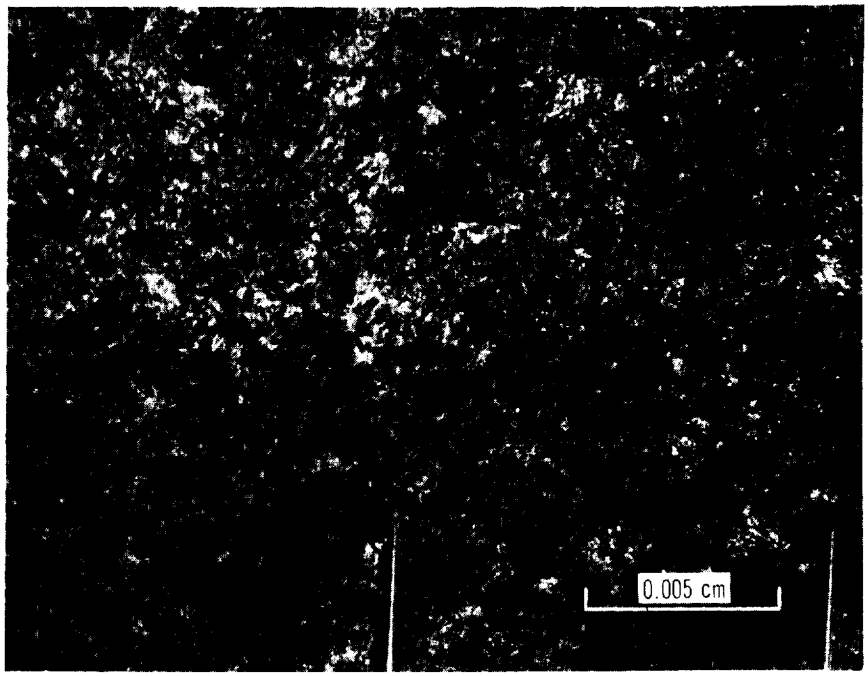
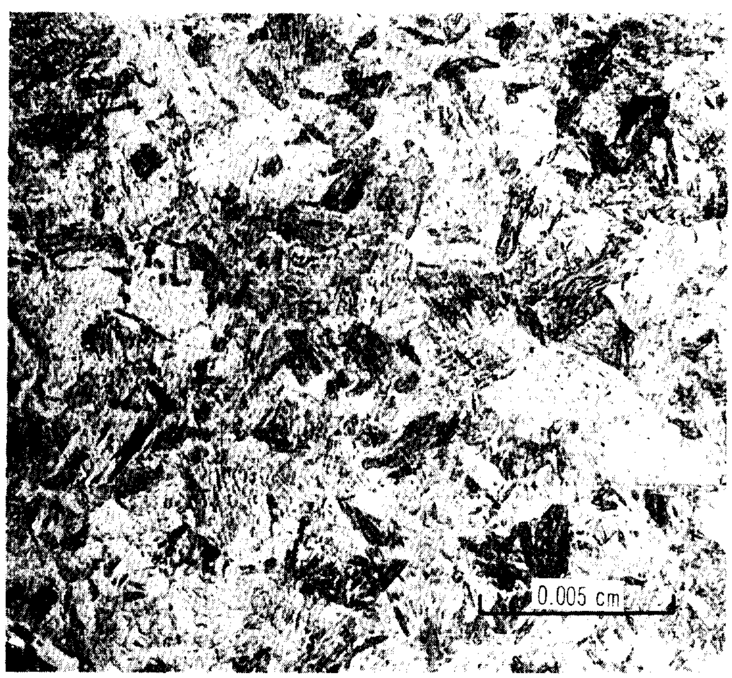


(b) Case structure. Small white areas are carbide particles.

Figure 5. - Microstructure of modified Vasco X-2 test gears.



(a) Carburized and hardened case of the VAR AISI 9310 gear showing high carbon fine grain martensitic structure.



(b) Core structure of VAR AISI 9310 gear showing low carbon refined austenitic grain size.

Figure 6. - Photomicrographs of case and core regions of test gears.

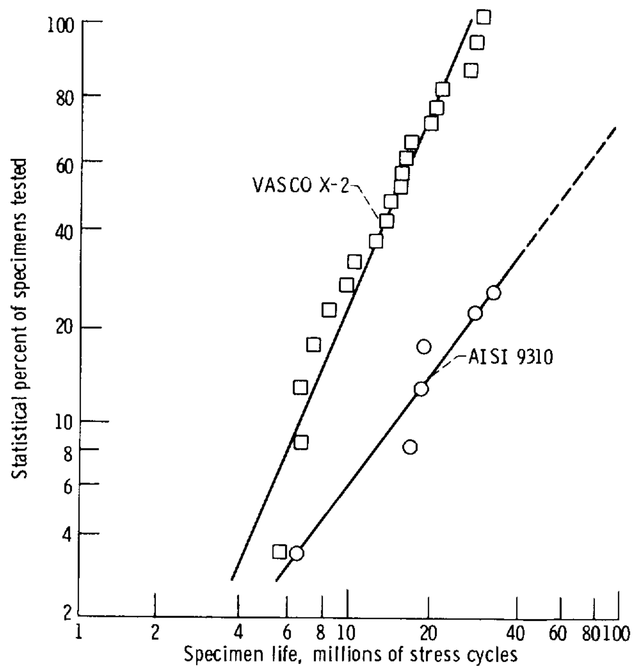


Figure 7. - Comparison of rolling-element fatigue lives of AISI 9310 and VASCO X-2 in rolling-contact tester. Speed, 25 000 stress cycles/min; maximum Hertz stress, 4823×10^6 N/m^2 (700 000 psi); lubricant, MIL-L-7808; temperature ambient.

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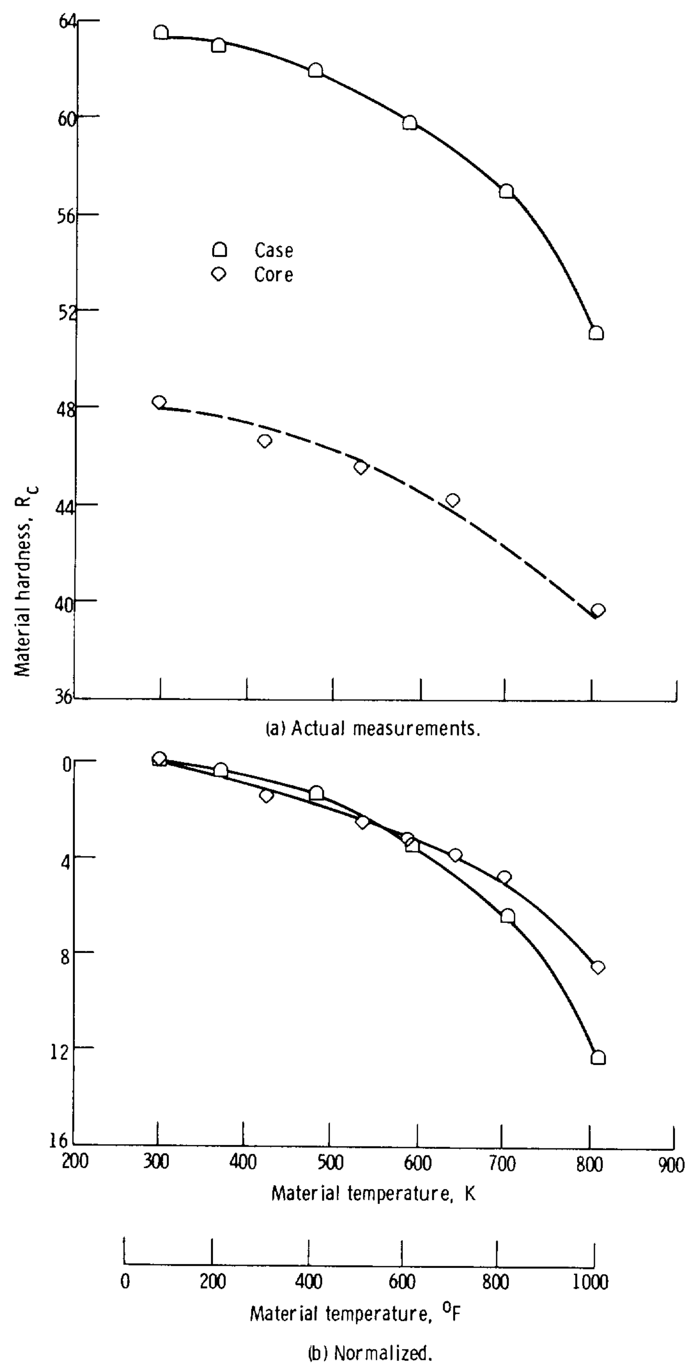

Figure 8. - Short-term hot-hardness characteristics of modified VASCO X-2.

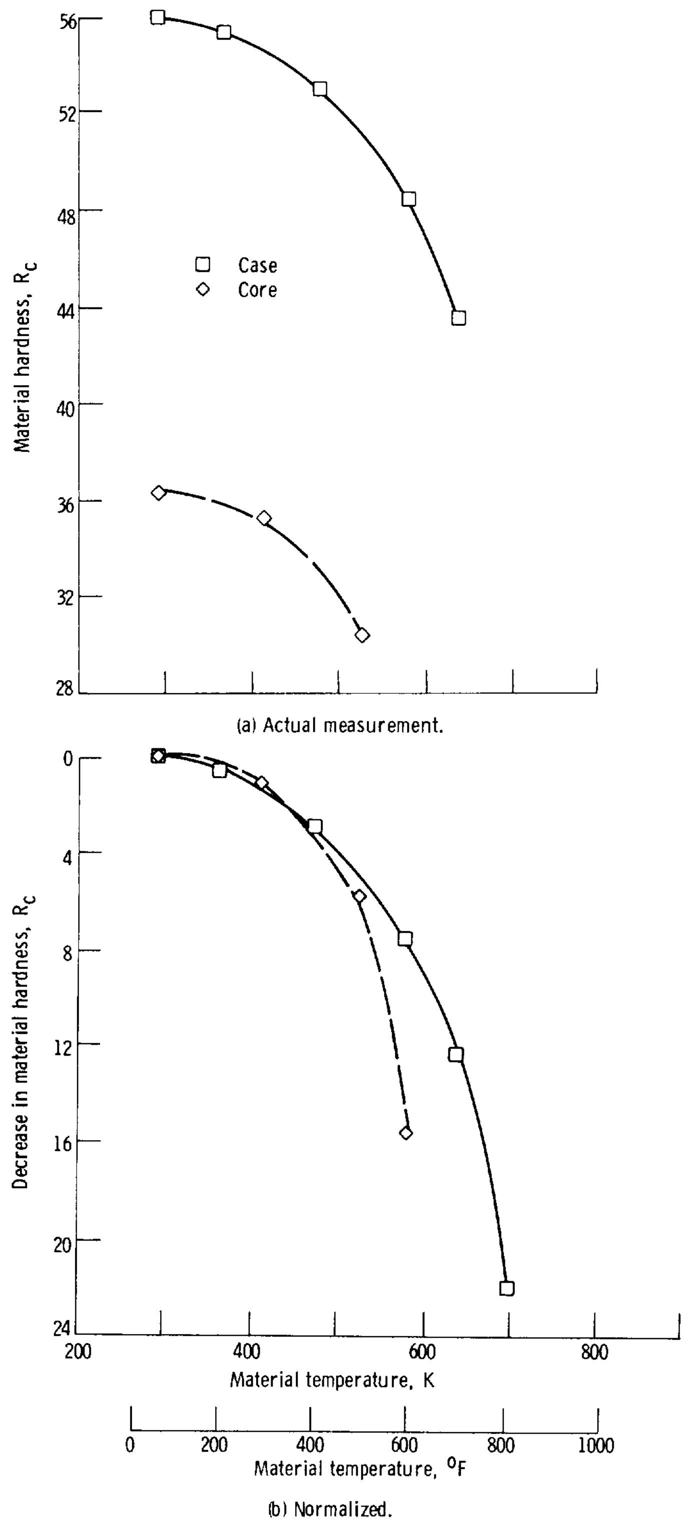

Figure 9. - Short term hot-hardness characteristics of AISI 9310.

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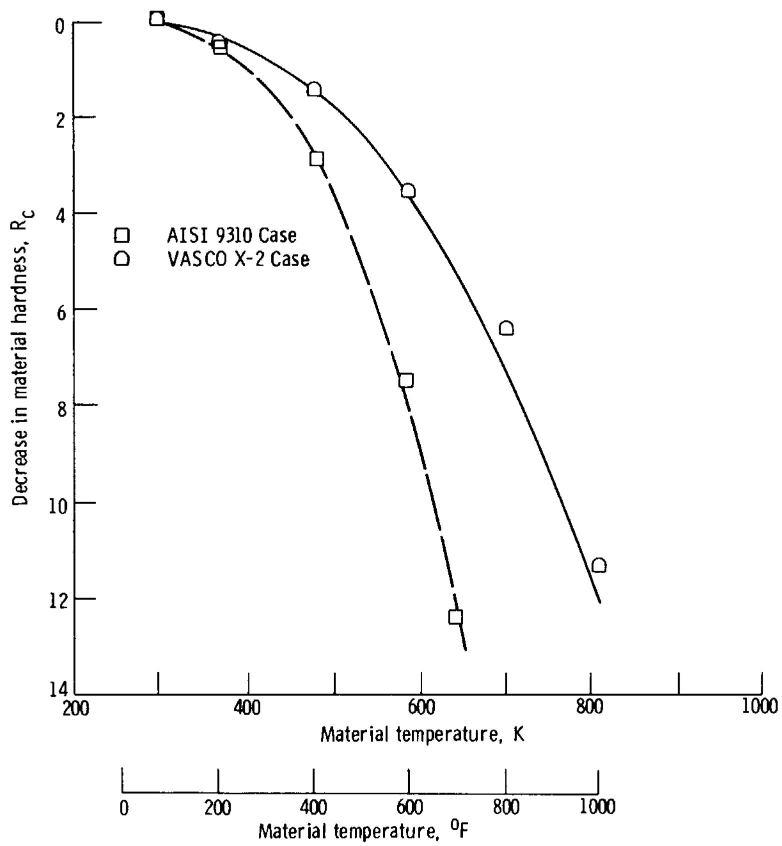

Figure 10. - Comparison of normalized short-term hot-hardness characteristics of AISI 9310 and modified VASCO X-2.

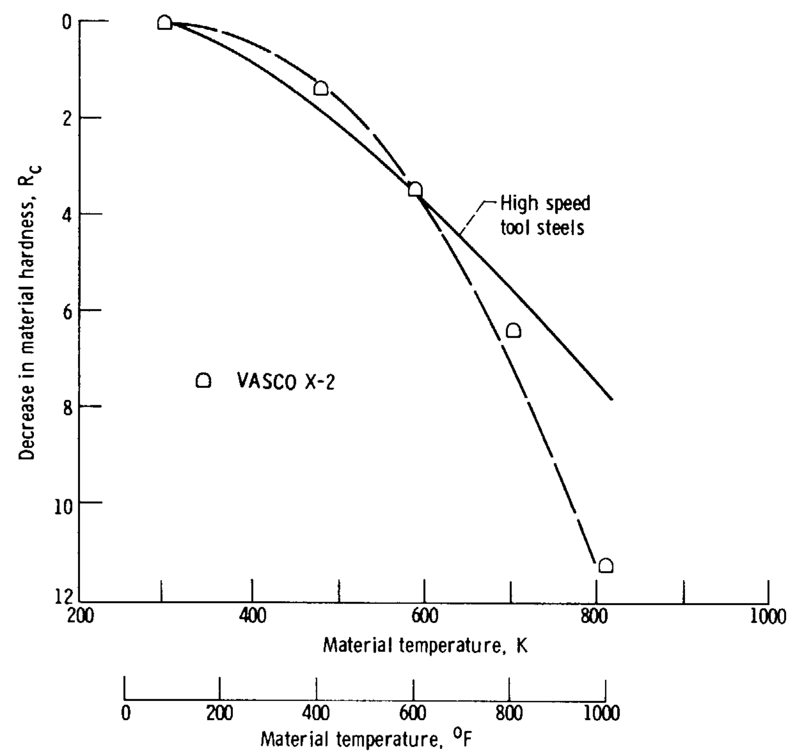

Figure 11. - Comparison of normalized short-term hot-hardness characteristics of modified VASCO X-2 and tool steels.

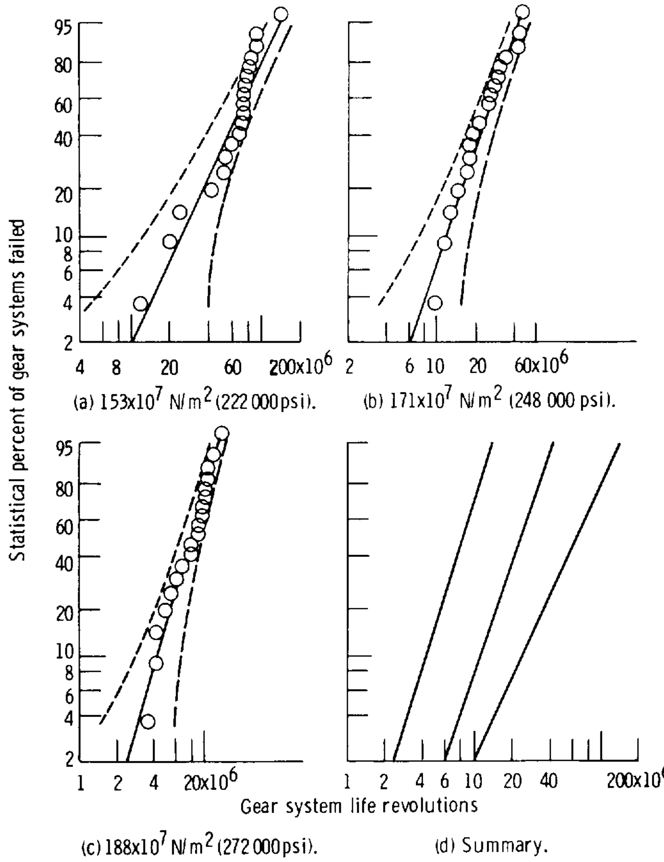

Figure 12. - Life of 8.39 cm (3.5 in.) pitch diameter VAR AISI 9310 spur gears. Speed, 10 000 rpm, lubricant superrefined naphthanic mineral oil; temperature, 350 K (170° F).

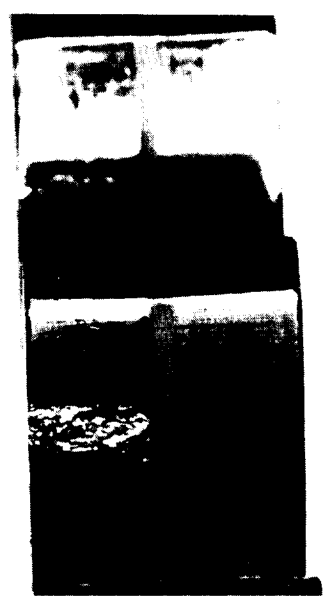

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Figure 13. - Representative fatigue spall of test gear material VAR AISI 9310 steel. Speed, 10 000 rpm; lubricant, superrefined naphthenic mineral oil with additive package.

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Figure 14. - Typical fracture of modified Vasco X-2 gear teeth.

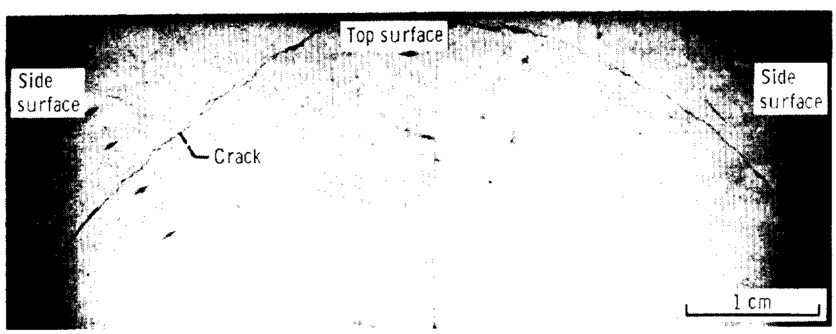

Figure 15. - Cross section of unfailed gear tooth from failed modified Vasco X-2 gear showing crack at each corner of tooth.

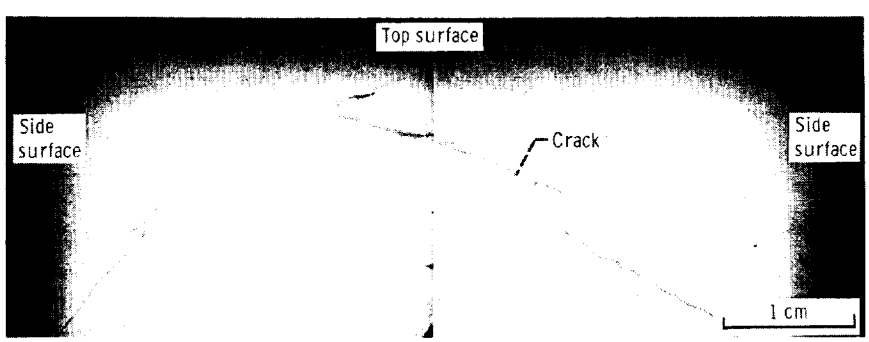

Figure 16. - Cross section of gear tooth from unrun modified Vasco X-2 gear showing crack formation.